

The environment of the unidentified gamma-ray source HESS J1507-622

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ABSTRACT

Context. The nature of the gamma-ray source HESS J1507-622 that is located significantly off-set from the Galactic plane is not ascertained to date.

Aims. Identifying the environment of an enigmatic object may help to constrain its nature.

Methods. The path of the line of sight of HESS J1507-622 through the Galaxy is compared to the characteristic length scales of stellar populations of different ages. Furthermore, for this object, the energy density in particles is contrasted to the magnetic field energy density and constraints on the distance based on equipartition between these two components are calculated.

Results. The line of sight of HESS J1507-622 reaches a minimum distance to the Galactic center at around a galactocentric distance of 5.3 kpc at about 300 pc off the Galactic disc. This location coincides with the scale length and width of stars with an age of 1.2 Gyr which could in principle be an indication that HESS J1507-622 is connected to a stellar population of similar age. For such a case the source appears to be strongly particle dominated. In a leptonic scenario, if a magnetic field in the source of $1 \mu\text{G}$ is assumed, equipartition between magnetic field and particles would be realized at a distance of $\gtrsim 1$ Mpc. This could indicate an extragalactic origin of this object. However, an extragalactic origin is challenged by the extension of the source.

Conclusions. The environment of HESS J1507-622 still remains elusive. For the case where this source belongs to a new class of gamma-ray emitters, the distribution of related objects (if existing) may help to settle the respective environment and distance scale.

Key words. pulsars: general – ISM: supernova remnants – gamma rays: galaxies – Radiation mechanisms: non-thermal

1. Introduction

Several unidentified very-high energy (VHE, $E > 100$ GeV) gamma-ray sources have been found by H.E.S.S. in a survey of the inner galaxy (Aharonian et al., 2008). One particular source appears to be exceptional since it is the only unidentified sources that is located significantly off-set from the Galactic plane (3.5° , Acero et al., 2011). This VHE emitter is connected to a high energy (HE, $100 \text{ MeV} < E < 100 \text{ GeV}$) counterpart (based on 24 month of *Fermi*-Lat data, Nolan et al., 2012) and potentially also to a faint, diffuse X-ray counterpart (Acero et al., 2011). The nature of the source has been disputed since its discovery. Domainko (2011a) concluded that the compactness of the source disfavors a supernova remnant (SNR) scenario. Domainko & Ohm (2012) analyzed a larger HE data set of 34 month from the *Fermi* satellite and found that the gamma-ray spectral energy distribution (SED) appears to be rather flat from the GeV to the TeV regime. In this paper it was further discussed that the measured gamma-ray SED, the compactness of the source and its off-set location from the Galactic plane challenge a pulsar wind nebula (PWN) scenario for HESS J1507-622. Vorster et al. (2013) fitted a PWN model to the multi-wavelength SED (using the result of 24 month of *Fermi* exposure obtained by Nolan et al., 2012) and concluded in favor for a PWN scenario. Acero et al. (2013) finally analyzed 45 month of

Fermi data above 10 GeV and placed this object in their non-PWN sample.

In this paper an alternative approach is adopted to explore the nature of HESS J1507-622. Its exceptional position is used to investigate the properties of the stellar environment along the line of sight of the source. Similar approaches have been applied to constrain the origin of enigmatic objects in the past. Studies of the stellar ages and stellar environments have extensively been applied to investigate the nature of the progenitors of supernovae Ia (e.g. Maoz et al., 2011) and short gamma-ray bursts (e.g. Berger, 2014). Prospects for the origin of the VHE gamma-ray source HESS J1747-248 have been presented based on its location in the vicinity of the Galactic globular cluster Terzan 5 (Abramowski et al., 2011; Domainko, 2011b). Finally, host galaxies of extragalactic gamma-ray emitters of BL Lac-type have been studied in depth (e.g. Cheung, 2003; Shaw et al., 2013).

This paper is organized in the following way: In Sec. 2 the Galactic stellar population along the line of sight of HESS J1507-622 is explored. In Sec. 3 other potential sources of VHE emission at Galactic off-plane locations and their relation to HESS J1507-622 are discussed. In Sec. 4 constraints on the distance to HESS J1507-622 based on equipartition between the energy densities in particles and magnetic fields are evaluated. And in Sec. 5 prospects for an extragalactic scenario for HESS J1507-622 are explored.

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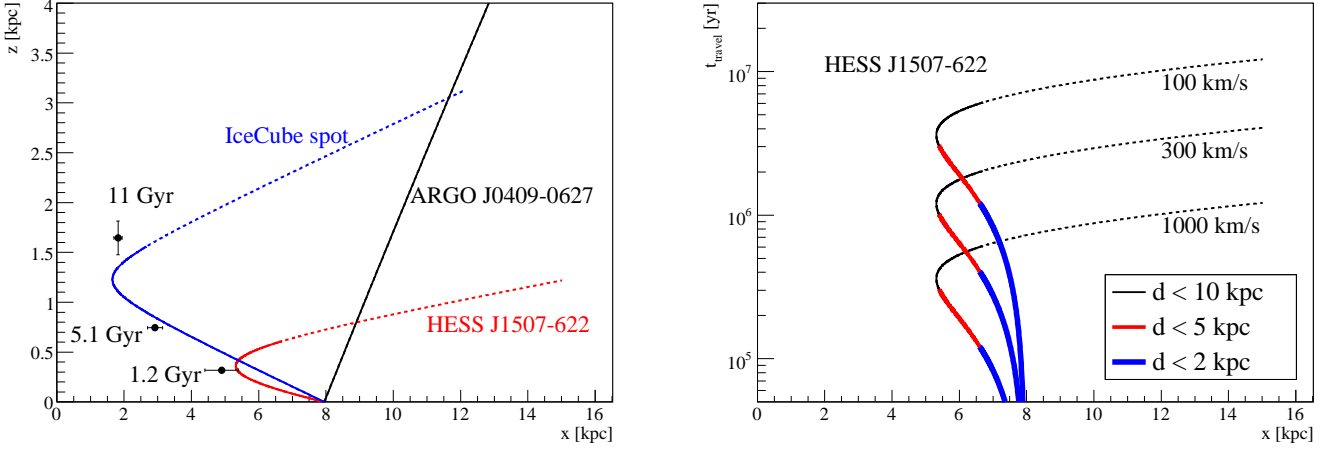


Fig. 1. The path of the line of sight of HESS J1507-622 through the Galaxy is shown in this figure. Left panel: Here the path of the line of sight is compared to the scale length of stellar populations with various ages (x is the galactocentric radius in the Galactic plane and z is the absolute height above the plane). For HESS J1507-622 the region where the path of the line of sight is closest to the Galactic center coincides with the scale length of a stellar population with age of about 1.2 Gyr (Stinson et al., 2013). For comparison also the line of sights for ARGO J0409-0627 and the spot with highest probability for being a VHE neutrino source are also shown. Solid lines indicate a source distance of less than 10 kpc (the distance to ARGO J0409-0627 within an absolute height above the Galactic plane of $\lesssim 4$ kpc is always shorter than 10 kpc). Right panel: Times of travel for a high space-velocity stellar population with various velocities perpendicular to the Galactic plane are shown along the line of sight of HESS J1507-622. The blue thick solid line indicates a source distance of less than 2 kpc, the red medium thick solid line indicates a source distance of less than 5 kpc and the black thin solid line indicates a source distance of less than 10 kpc.

2. Parent stellar populations along the line of sight of HESS J1507-622

2.1. Parent stellar population

In the Galaxy, old stars lie in thick distributions around the plane with short disk scale length (e.g. Stinson et al., 2013). For younger stellar populations the width of the distribution decreases and the disk scale length increases. The compactness of HESS J1507-622 suggests a distance to the object of several kpc (e.g. Hinton & Hofmann, 2009; Domainko & Ohm, 2012) that is comparable to the characteristic length-scales of the stellar population of the Galaxy. Therefore, the line of sight through the Galaxy of HESS J1507-622 can in principle be compared to the characteristic length scales of the distributions of stellar populations of different ages (see Fig. 1, left panel). This line of sight reaches a minimal distance to the galactic center at a galactocentric distance of 5.3 kpc at about 300 pc off the Galactic disc (assuming a Galactic center – sun distance of 7.94 kpc, Eisenhauer et al., 2003). For a bulge-like stellar distribution, there the line of sight passes through the region with the highest stellar density. The location of minimal galactocentric distance coincides with the scale length and width of stars with an age of 1.2 Gyr (Stinson et al., 2013) which could in principle be an indication that HESS J1507-622 is connected to a stellar population of similar age. For comparison, for supernovae Ia, a prompt channel is found (age < 420 Myr) together with a population that is delayed by > 2.4 Gyr (Maoz et al., 2011). For a further comparison, the stellar ages connected to short gamma-ray bursts span from a few tens of Myr to about 4 Gyr (Berger, 2014). It has to be noted that a few off-plane objects of the same type (if existing) would

be needed for a more conclusive comparison with stellar populations of different ages (see Sec. 3).

2.2. High space-velocity stellar population

In the previous paragraph it has been assumed that HESS J1507-622 shares the typical velocity distribution of its parent stellar population. However, some particular objects travel with much larger space velocities (pulsars for example show a mean three dimensional velocity of 380^{+40}_{-60} km s $^{-1}$, Faucher-Giguère & Kaspi, 2006). For such a case constraints on the age of the VHE emitter can be estimated from the time of travel to the observed location if it is assumed that the object was born close to the Galactic plane. The time of travel as a function of location in the Galaxy for HESS J1507-622 is shown in Fig. 1 (right panel). Estimated travel times range from $\gtrsim 10^5$ years for velocities perpendicular to the Galactic plane of ≈ 1000 km s $^{-1}$ to $\approx 10^7$ years for moderate velocities of ≈ 100 km s $^{-1}$ and multi-kpc distances. Only the shorter estimates of the travel times would be compatible with the ages of observed PWNe (Kargaltsev et al., 2013). However, massive high-velocity stars with lifetimes $\gtrsim 10^7$ years would be able to reach such off-plane locations. For constraints on the distance to HESS J1507-622 see Sec. 4.

3. Other potential sources of VHE emission at Galactic off-plane locations

In contrast to other unidentified VHE gamma-ray sources that are located at the Galactic plane (see Aharonian et al., 2008), HESS J1507-622 is located significantly off-set from it. This object could simply be an outlier to the usual dis-

tribution of sources, or it could be a representative of a class of VHE gamma-ray emitters with broader distribution around the Galactic plane. In this section indications for an off-plane source population are explored. Furthermore, properties of potential VHE emitters at locations off the Galactic plane are briefly reviewed. The relation between these source candidates and HESS J1507-622 is unclear at the moment. However, if some of these objects are of similar type as HESS J1507-622, their position on the sky may help to further constrain the environment of this source.

3.1. *ARGO J0409-0627*

Recently the ARGO-YBJ collaboration has reported on a survey of the northern sky in the VHE gamma-ray regime (Bartoli et al., 2013). In this survey one source candidate without clear identification has been found with large offset from the galactic plane: ARGO J0409-0627. It has to be noted that this source candidate has the lowest post-trial significance ($< 3\sigma$) of all presented sources. At a position of $l = 198.5^\circ$, $b = -38.7^\circ$ it seems not to follow the distribution of Galactic stellar populations (see Fig. 1 left panel). Its position coincides with a group of galaxies (SDSS J040922.92-062636.4, SDSS J040921.13-062936.5, SDSS J040912.63-062546.6, SDSS J040914.54-063030.7, Adelman-McCarthy et al., 2008, at a common redshift of 0.12)¹, however a physical association is unclear at the moment.

3.2. *IceCube neutrino sources*

The IceCube collaboration has detected evidence of extraterrestrial neutrinos in the TeV-PeV regime (Aartsen et al., 2013). With the current data, the distribution of these neutrino events is consistent with an isotropic distribution on the sky, with a spot of highest probability for being a neutrino source located at $l = +12^\circ$, $b = -9^\circ$. In the case that the VHE neutrino sky comprises sources rather than truly diffuse emission it is expected that neutrino sources are linked to VHE gamma-ray sources (e.g. Kappes et al., 2007) and for the detected neutrino events a correlation with unidentified VHE gamma-ray sources has already been suggested (Fox et al., 2013). For the purpose of this paper it is assumed that the VHE neutrinos originate from discrete sources. Most relevant for the discussion in this paper is the fact that the distribution of extraterrestrial neutrinos seems not to be strongly peaked at the galactic plane. Additionally, the gamma-ray SED of HESS J1507-622 can reasonably be fit by a hadronic model (Domainko & Ohm, 2012). If this is the actual emission process of the source, that would imply neutrino emission from objects of similar type. However, so far there is no positional coincidence of any neutrino event with the location of HESS J1507-622.

In Fig. 1 (left panel) the line of sight of the neutrino spot through the galaxy is compared to the distribution of stellar populations of various ages. If located close to its minimal distance to the Galactic center the position of this spot would coincide with the characteristic length scale of a very old stellar population. However it has to be noted that the positional uncertainties of shower-like neutrino events is rather large ($\gtrsim 10^\circ$, Aartsen et al., 2013). It has to be

further noted that the distance scale to the VHE neutrino emission sites is not known to date. For implications of an extragalactic scenario see Sec. 5.

4. Comparison between the energy density in particles and the magnetic field

In this section the particle energy density of HESS J1507-622 as function of distance is derived and is compared to the energy density in the magnetic field. Furthermore, constraints on the distance of the object are evaluated based on the assumption that the particle energy density approximately equals the energy density in the magnetic field. Evolved sources may approach this kind of equilibrium state (see Longair, 1994, for a discussion).

4.1. *Leptonic scenario*

In a leptonic scenario, the energy in electrons energetic enough to produce gamma-ray emission through inverse-Compton up-scattering of cosmic microwave background photons amounts to $E_e(d) = 3 \times 10^{47} (d/1 \text{ kpc})^2 \text{ erg}$ with d being the distance to the source (if a considerable fraction of the total energy in particles is stored in lower energy electrons, the total energy increases accordingly, see Domainko & Ohm, 2012). For comparison, Vorster et al. (2013) found an energy in particles of about $1.5 \times 10^{48} \text{ erg}$ for a distance of 6 kpc (about a factor of 7 smaller than the estimate of Domainko & Ohm, 2012). Since Domainko & Ohm (2012) also included spectral points below 10 GeV for the estimate of the energy in electrons, this value is used for the purpose of this paper. The volume of the object scales with $V(d) = 4\pi/3 \times (d \times \tan \theta)^3$ with $\theta = 0.15^\circ$ being the angular radius of the source. Using these two relations, the energy density in electrons is given by $u_e(d) = E_e(d)/V(d)$. The particle energy density scales with distance as d^{-1} . It is plotted in Fig. 2 left panel and there it is compared to the energy density in magnetic fields of strength 10 μG , 100 μG and 1 mG with $u_B = B^2/8\pi$. It is found that for a Galactic origin of HESS J1507-622 ($d \lesssim 20 \text{ kpc}$) the particle energy density would exceed the energy density in a magnetic field of 10 μG .

4.2. *Hadronic scenario*

For a hadronic scenario the energy in protons is given by $E_p(d) = 4\pi d^2 \times F_\gamma \times \tau_{pp}(d)$. Here $F_\gamma \approx 8.2 \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$ is the gamma-ray flux above 1 GeV (Domainko & Ohm, 2012) and, $\tau_{pp} = 3 \times 10^7 n^{-1}(d)$ years, is the cooling time of hadronic cosmic rays for a given density of target material n . The density of target material varies with distance to HESS J1507-622. Since the line of sight towards HESS J1507-622 moves to larger Galactic heights below the plane with increasing distance d , the density of target material as a function of distance drops monotonically (see Domainko, 2011a). Here the density of target material as a function of absolute height off the Galactic plane z is adopted to be (Dickey & Lockman, 1990):

$$n(z) = 0.395 e^{\frac{-z}{127 \text{ pc}}} + 0.107 e^{\frac{-z}{318 \text{ pc}}} + 0.064 e^{\frac{-z}{403 \text{ pc}}} \text{ cm}^{-3} \quad (1)$$

If now the relation $z = d \times \sin 3.5^\circ$ (3.5° being the angular distance of HESS J1507-622 from the Galactic plane)

¹ <http://ned.ipac.caltech.edu/>

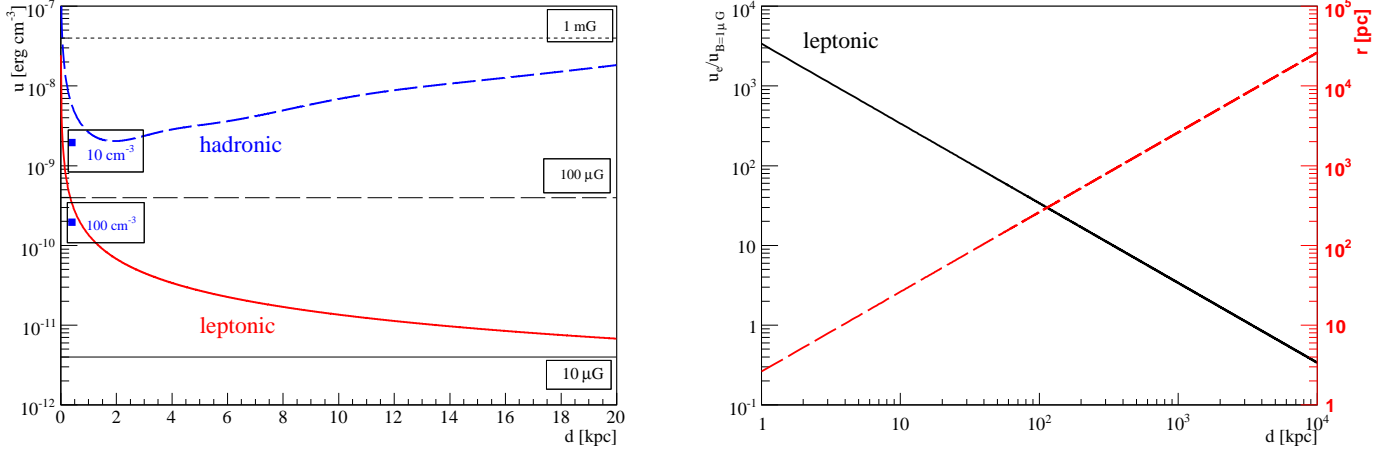


Fig. 2. Left panel: the energy density in particles in HESS J1507-622 as a function of distance is shown (for details see main text). Additionally, the energy density for a hadronic scenario for the case where the source is located on the edge of a molecular cloud at a distance of 400 pc (Acero et al., 2011) for a density of target material of 10 cm^{-3} and 100 cm^{-3} is plotted as blue dots. For comparison, the energy density of magnetic fields with strength $10 \mu\text{G}$, $100 \mu\text{G}$ and 1 mG is given. Right panel: The ratio of energy density in particles and energy density in the magnetic field as a function of distance is shown as a solid black line for the case of $1 \mu\text{G}$. These two energy densities roughly equal at a distance of about 4 Mpc. On the right hand y-axis the source extension as a function of distance is shown with a dashed red line. At a distance of 4 Mpc, the source would extend to $\approx 10 \text{ kpc}$.

is substituted in $n(z)$, the density of target material as function of distance and thus also $E_p(d)$ can be calculated. By using the volume of the source $V(d)$ from the previous paragraph, the energy density in particles is given by $u_p(d) = E_p(d)/V(d)$. It is plotted in Fig. 2 left panel. Additionally, since HESS J1507-622 is located at the edge of a molecular cloud at a distance of 400 pc (see Acero et al., 2011), the energy density for this distance assuming a density of target material of 10 cm^{-3} and 100 cm^{-3} is also shown in Fig. 2. From Fig. 2 left panel it is evident that for a hadronic scenario the particle energy density for a Galactic origin of HESS J1507-622 would in most cases exceed the energy density in a magnetic field of $100 \mu\text{G}$.

4.3. Constraints on the distance

The calculated energy density in particles can be compared to the energy density in the magnetic field estimated for HESS J1507-622. From SED fitting Domainko & Ohm (2012) and Vorster et al. (2013) constrained the magnetic field for a leptonic scenario in HESS J1507-622 to $B \lesssim 1 \mu\text{G}$. The resulting magnetic field energy density $u_B \lesssim 4 \times 10^{-14} \text{ erg cm}^{-3}$ is several orders of magnitude lower than the energy in particles for typical Galactic distances (see Fig. 2 right panel). Thus for a Galactic origin of HESS J1507-622 the source appears to be strongly particle dominated (it has to be noted that young PWNs are also particle dominated, Torres et al., 2014). For a leptonic scenario a situation where particle energy density approximately equals the energy density in the magnetic field is only realized for distances of $d \gtrsim 1 \text{ Mpc}$ (even more distant if a considerable fraction of total energy is stored in low energy electrons that do not radiate in gamma-rays, Domainko & Ohm, 2012). For comparison, using the model of Vorster et al. (2013) an equipartition distance of 180 kpc would be found (for $B = 1.7 \mu\text{G}$). Since this distance is

larger than the size of the Galaxy, in the next paragraph extragalactic scenarios are explored for HESS J1507-622. In a hadronic scenario equipartition between particles and magnetic fields is not achieved out to cosmological distances ($\gtrsim 100 \text{ Mpc}$) for ambient densities of target material $\lesssim 0.1 \text{ cm}^{-3}$.

5. Prospects for an extra-galactic scenario

In general extragalactic scenarios are challenging due to the large energetics needed to power the source and due to the very extended nature of the emission. About $3 \times 10^{53} (d/1 \text{ Mpc})^2 \text{ erg}$ in electrons would be needed in a leptonic scenario and the source would spread over $2.6 (d/1 \text{ Mpc}) \text{ kpc}$ (see Fig. 2, right panel).

5.1. Constraints from the source extension

To date only very few sources with multi-kpc extension have been detected in the GeV band. Very extended gamma-ray sources are the Centaurus A lobes (Abdo et al., 2010) and the Fermi bubbles (Su et al., 2010). However, no object with such a large spatial dimension has been found in the TeV regime so far. The extension of leptonic TeV sources is expected to be limited to few tens of parsecs by radiation losses (Hinton & Hofmann, 2009).

An alternative model for very extended sources at extragalactic distances is provided by a scenario where VHE gamma-rays produce a halo of e^+ and e^- pairs around the source (Aharonian et al., 1994). More specifically, gamma-rays with energies $\gtrsim 100 \text{ TeV}$ may produce rather compact halos of size $\lesssim 1 \text{ Mpc}$. The detection of multiple-10s of TeV to PeV neutrinos (Aartsen et al., 2013) indicates the emission of gamma-rays (if not absorbed inside the source) with such energies. These sources (especially if they emit

isotropically) could in principle be surrounded by compact pair halos radiating in the TeV regime.

Such pair halos at a distance of $\lesssim 300$ Mpc would appear with roughly comparable extension as HESS J1507-622. In a scenario where energy in particles roughly equals the energy in the magnetic field of $1 \mu\text{G}$ (see Sec. 4), HESS J1507-622 could be located at a coarsely compatible distance if a major part of its particle energy is stored in electrons not energetic enough to radiate in the gamma-ray regime (see Domainko & Ohm, 2012). Alternatively, HESS J1507-622 could also be located at a coarsely compatible distance, if a lower magnetic field for this source is considered for the evaluation of equipartition between particles and magnetic field (i.e. the diffuse X-ray source in the magenta circle of Fig. 3 of Acero et al., 2011, is not the synchrotron counterpart to HESS J1507-622).

The caveat for this interpretation is that the nature and distance scale of the VHE neutrino emitters are not known to date and that plasma effects may suppress the electromagnetic cascade that form pair halos (Broderick et al., 2012; Schlickeiser et al., 2012). More generally, finally it has to be noted, that there is no evidence that equipartition is actually established in HESS J1507-622.

5.2. Constraints on the energetics

Super-massive black holes (SMBHs) are the most common class of extragalactic VHE gamma-ray emitters (see Hinton & Hofmann, 2009, for a review). In this section it is evaluated whether any SMBH located in the line of sight of HESS J1507-622 would be able to power this VHE gamma-ray source.

5.2.1. Black hole masses

The mass of a SMBH is linked to the mass and thus luminosity of its host galaxy (e.g. Magorrian et al., 1998; Häring & Rix, 2004). Consequently from the brightness of any galaxy in the direction of HESS J1507-622 the mass of its SMBH as a function of luminosity distance d_L can be estimated. Here the K-band brightness of potential galaxies is used since HESS J1507-622 is located rather close to the Galactic plane and infrared luminosities are less affected by absorption due to inter-stellar dust. The infrared source closest to the centroid of HESS J1507-622 is 2MASS J15075554-6222336 ($m_K = 14.39$ mag, corrected for galactic extinction of $A_K = 0.505$, Schlafly & Finkbeiner, 2011) located at an angular distance of $230''$. The brightest infrared source inside the extend of the VHE source is 2MASS J15070879-6216441 ($m_K = 11.16$ mag, again corrected for extinction) located at an angular distance of $517''$ (Cutri et al., 2003)². For the rest of this section it is assumed that these two sources represent galaxies harboring SMBHs. The mass of the SMBH of these hypothetical galaxies as function of luminosity distance can be estimated from the following relations (Marconi & Hunt, 2003):

$$\log M_{\text{BH}}(d_L) = 8.21 + 1.13 (\log L_K(d_L) - 10.9) \quad (2)$$

with

$$\log (L_K(d_L)/L_{K,\odot}) = 0.4 (3.28 - M_K(d_L)) \quad (3)$$

and

$$M_K(d_L) = m_K + 5 \log (d_L) - 5 \quad (4)$$

Here, $L_K(d_L)$ is the luminosity of the host galaxy in the K-band and $M_K(d_L)$ is the absolute K-band magnitude of the host galaxy as function of the luminosity distance ($M_{K,\odot} = 3.28$ mag is the absolute K-band magnitude of the sun). The masses of these hypothetical SMBHs as function of distance are plotted in Fig. 3.

5.2.2. Comparison to the Eddington luminosity

With these calculated SMBH masses, constraints on their luminosities in electromagnetic radiation can be made. The maximum possible continuous luminosity radiated by a black hole is given by the Eddington luminosity that scales with black hole mass M_{BH} as $L_{\text{Edd}} \approx 10^{38} (M_{\text{BH}}/1M_{\odot}) \text{ erg s}^{-1}$. With this input L_{Edd} as a function of luminosity distance for any potential SMBH in the direction of HESS J1507-622 can be calculated and can be compared to the gamma-ray luminosity of the source (see Fig. 3). Since HESS J1507-622 is an extended object it is expected that the emission is not beamed and can thus be compared to L_{Edd} . It is found that HESS J1507-622 would have to radiate on the level of 1% (2MASS J15075554-6222336) and 0.05% (2MASS J15070879-6216441) of L_{Edd} of a SMBH in these hypothetical galaxies. To conclude, a scenario where HESS J1507-622 is powered by a SMBH is in principle energetically possible. However, in this case, the extension of the source still has to be explained (see Sec. 5.1). Nevertheless, if similar sources as HESS J1507-622 will be found at large Galactic latitudes, this may indicate an extragalactic scenario for these objects (see Sec. 3).

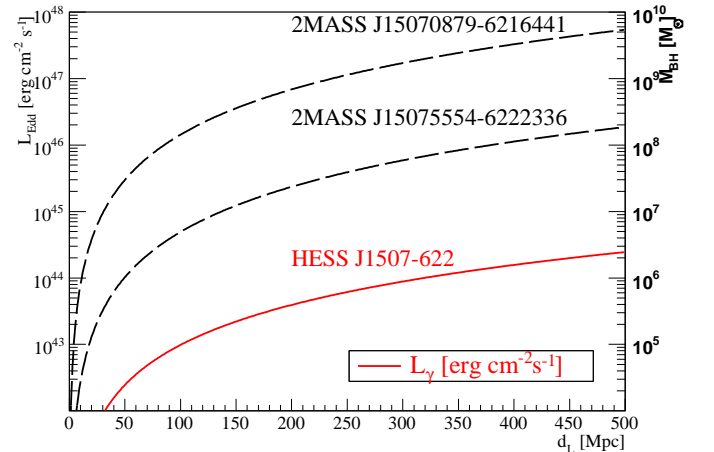


Fig. 3. The gamma-ray luminosity of HESS J1507-622 is plotted as a function of luminosity distance with a red solid line. For comparison, the mass and Eddington luminosity of a hypothetical SMBH in 2MASS J15075554-6222336 and 2MASS J15070879-6216441 is shown as a function of distance with dashed black lines (for more details see main text).

² <http://simbad.u-strasbg.fr/simbad/>

6. Summary and outlook

In this paper the environment of the unidentified off-plane gamma-ray source HESS J1507-622 is explored. Since the location on the sky of this object is unique with respect to the positions of other unidentified VHE gamma-ray sources, examining the environment may give additional insights in its nature. However, with the currently available informations the surroundings of HESS J1507-622 could not be identified.

For a Galactic origin of this source its location may indicate a parent stellar population as old as 1 Gyr. In this case the source appears to be rather strongly particle dominated. In principle, particle dominance seems to be possible for Galactic VHE gamma-ray emitters, with young PWNe also showing this feature. However, in a leptonic scenario, a case where energy in particles exceeds the energy in the magnetic field by a factor of 100, would still require a distance of about 40 kpc for this object (for $B = 1 \mu\text{G}$).

A situation where the energy density in particles roughly equals the energy density in the magnetic field for HESS J1507-622 would place this object at an extragalactic distance ($\gtrsim 1$ Mpc). Such a scenario face the challenge to explain the connected rather large extension of the source. For the case where HESS J1507-622 belongs to a new class of gamma-ray emitters, evaluation of the distribution of related objects (if existing) may further help to constrain the environment of HESS J1507-622.

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